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A 3D Printed Wearable Glove with Inflatable Chambers

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Abstract. For individuals with limited hand mobility due to injury or surgery, active hand-rehabilitation is critical for regaining range of motion, flexibility, and strength. This study presents a novel wearable glove designed to enhance active hand rehabilitation therapy. The wearable glove, fabricated using three-dimensional printing (3D printing) with flexible thermoplastic polyurethane (TPU 60) and durable tough polylactic acid (tough PLA), features adjustable inflatable chambers targeting the torque applied to metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints. These chambers enable personalized resistance training by allowing therapists to adjust air pressure within the chambers. The variation of stiffness and resistance force exerted by the chambers, as well as torsional stiffness at the MCP and PIP joints during finger bending, are investigated. This research contributes to the development of pressure-based personalized resistance training for hand rehabilitation. Results indicate that the adjustable chambers in the wearable device offer a promising approach to enhance hand rehabilitation.

Keywords: Active hand rehabilitation, Inflatable chamber, Variable stiffness, Pressure-based resistance training.

1 Introduction

The growing need for rehabilitation and assistance due to an aging population and rising stroke cases has led to significant research in wearable devices. These devices offer varying degrees of support, aiding both activities of daily living (ADLs) and rehabilitation processes [1]. The hand is a vital human limb, and its functionality plays a crucial role in everyday activities. Rehabilitation of the hand becomes essential for individuals facing disabilities arising from various sources, including medical conditions such as injuries or stroke, and physical therapy, a branch of medicine, is relevant in this field. Therapists utilize repetitive exercise training with specific intensity levels to help patients regain hand mobility, strength, and functionality. Therapists employ two main approaches to help people with hand dysfunctionality: active and passive therapy [2]. Active therapy emphasizes patient participation in exercises to regain hand function, strength, and coordination. Passive therapy, on the other hand, uses external devices to move the hand joints without requiring active effort [3].

Although active therapy is fundamental for improving joint mobility and avoiding muscle contractures, conventional devices with fixed stiffness find it difficult to replicate the natural movement patterns of the human body [4]. This limitation arises because they are designed to have either high stiffness, which is good for precise positioning but makes it difficult for users to interact with them, or low stiffness, which prioritizes safety but sacrifices control over the device's movements. This fixed compliance can lead to discomfort and hinder patient progress by failing to adapt to his/her increasing strength. Current attempts to address this issue, such as springs with different tensions, provide limited adjustability. Variable stiffness mechanisms offer a more promising solution. These mechanisms allow passive devices to adapt their resistance in real-time, mimicking human muscles and creating a more natural and effective rehabilitation experience [5,6]. The development of variable stiffness devices presents challenges like increased weight and complexity. However, research in this area holds exciting possibilities, especially when combined with active therapy [7].

This paper describes the design and characterization of a wearable glove featuring a composite structure. This structure combines a base glove with Velcro straps and integrated inflatable chambers with customizable variable stiffness, specifically tailored for active hand rehabilitation therapy. This design allows patients to actively participate in exercises while simultaneously receiving the adaptable resistance of variable stiffness mechanisms. Through this innovative approach, we hope to create a more natural, effective, and comfortable hand rehabilitation experience. The CAD model and prototype of a wearable glove that integrates multiple variable stiffness chambers is shown in Fig. 1.

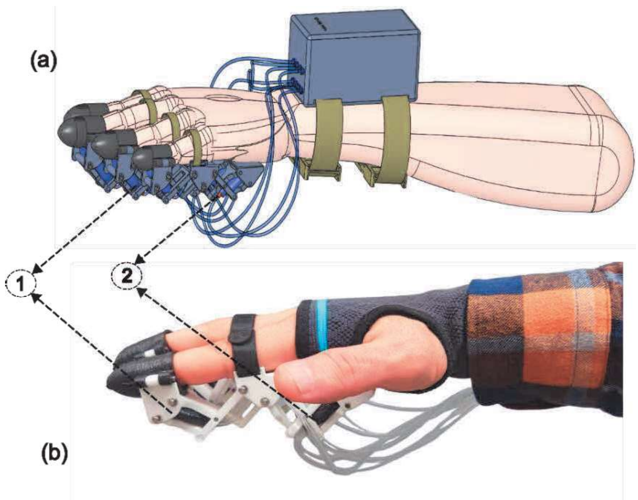

Fig. 1. Overview of the hand glove: (a) 3D CAD model with control box and inflatable chambers (1) forward, (2) backward. (b) Side view of the prototype.

2 Functional design and prototyping

A first critical factor in designing a comfortable and effective rehabilitation glove is ensuring that it replicates natural finger movement. To achieve this, the mechanism employs the principle of remote center of motion (RCM) for its finger joints. Unlike the traditional approach that places revolute joints coincident with the anatomical ones (MCP and PIP joints), placed laterally with respect to each finger, the RCM approach strategically positions the mechanical revolute axis away from these points. Fig. 2(a) shows the double parallelogram structure of the rehabilitation device index finger, and highlights the position of the RCMs. This design ensures that each rigid body of the device that is in contact with a finger phalange rotates with respect to the following one about a fixed virtual point. This way any relative sliding between the user's finger and the mechanical device during flexion and extension movements is minimized.

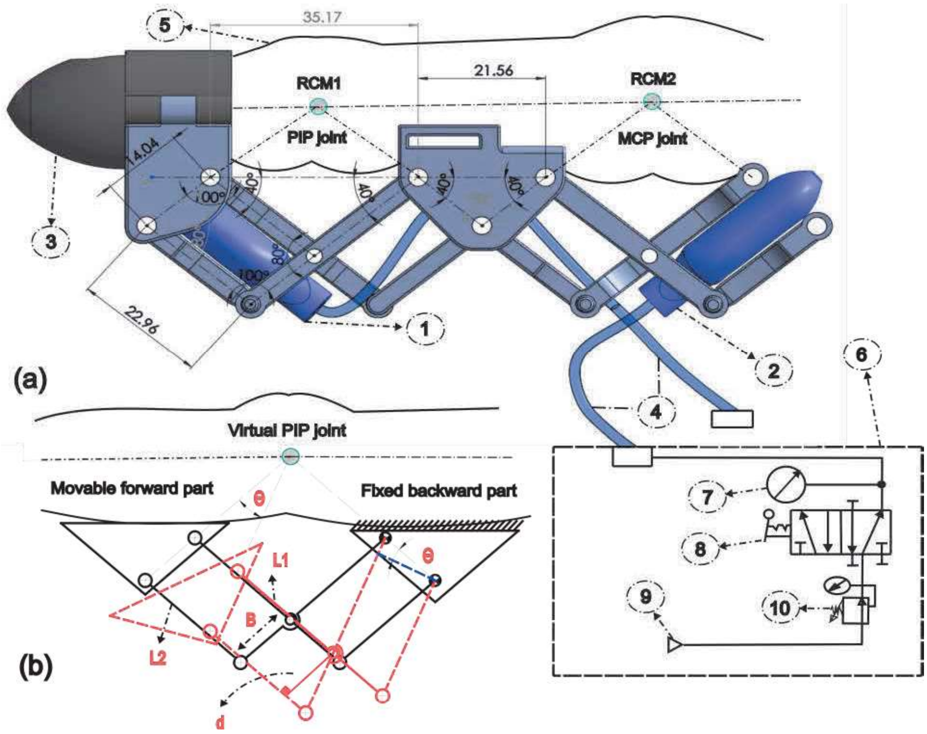

Fig. 2. Index finger structure. (a) Side view with dimensions (mm). (b) Rotation mechanism. Numbers correspond to: 1 = forward chamber, 2 = backward chamber, 3 = thimble, 4 = air tube, 5 = index finger, 6 = pneumatic system, 7 = pressure sensor, 8 = hand lever valve, 9 = air supply, 10 = air regulator.

A second requirement relates the need to provide the rehabilitation device with a customizable bending stiffness. To this aim, inflatable chambers were integrated into the device mechanical structure, as shown in Fig. 2(a). In particular, two chambers were confined between the mechanism rigid links, in order to be squeezed during the bending motion. Chambers having various geometries and made up of various materials were designed and manufactured by a 3D printer. A chamber with a 0.9 mm wall-thickness (Fig. 3. a, b, c), an extensive pillow-shaped contact area, made up of TPU 60 emerged as the ideal design to overcome tightness and encumbrance problems.

Fig. 3. Design and prototypes of chambers and thimbles. (a), (c) showcase CAD models, while (b) and (d) depict prototypes of chambers and thimbles, respectively.

As a wearable device, the last design requirement of the glove is to provide a comfortable fit to prevent any discomfort or fatigue. The wearer's comfort is achieved choosing a combination of soft and rigid structures for the wearable glove, ensuring that each part feels at ease within the maximum range of natural hand motion. The glove cap, which comes into contact with the user's fingertip, was manufactured using deformable and soft TPU to guarantee both comfort and compliance, as illustrated in Fig. 3(d). Following this, the rigid structure is made of tough PLA, complementing the soft structure.

2.1 Bending stiffness customization

Fig. 2(b) illustrates the working principle of the variable stiffness mechanism for the PIP joint of the index finger (similar mechanisms are employed for other finger joints). Two inflatable chambers are positioned between two rigid links. For instance, in the PIP joint, the forward chamber connects directly to the movable forward part representing the fingertip thimble and two rigid links. A hand lever valve is used to create a closed system comprised of the chambers and the air hoses. This system is initially pressurized to a specific value (P_i) using the valve. As shown in Fig. 2(b), when the finger bends at the PIP joint, the finger bending angle (θ) gradually increases, and the distance (d) between the designated links (L_1 and L_2) gradually decreases, as described in Eq. (1).

$$d = B \,.\, cos(\theta) \tag{1}$$

This decrease in spacing causes a reduction in the chamber and pipe volume, leading to an increase in internal air pressure. The resulting chamber stiffness is related to the compression law of the air volume, and by fixing the value of the initial pressure (P_i), it can be adjusted. This ability to achieve various stiffness levels for both chambers plays a crucial role in enhancing the effectiveness of the wearable glove in finger rehabilitation procedures. Using a pressure sensor, the pressure trend inside the closed volume can be monitored for stiffness control purposes.

3 Experimental Setup

Fig. 4 depicts the setup designed to assess the internal pressure, resistance force, and torsional stiffness of the structure at various finger bending angles ($0° \leq \theta \leq 45°$). The hand-operated pneumatic valve isolates the system after chambers are initially inflated to a certain pressure. Tests were carried out keeping fixed on an aluminum support the inner rigid part of the device and applying a bending force to the middle one, to cause its rotation about the device second virtual joint (RCM2 of Fig. 2). During the test, air hoses connected to the chambers pressurize them. The bending force was applied perpendicularly to the displaced rigid body, whatever was the pose of the latter, in order to keep its arm with respect of the device virtual joint constant during the test. The procedure was repeated keeping fixed the middle rigid part and causing the rotation of the outer one. This way, the resistant torque generated by the device during bending about each virtual joint was finally obtained. A MPX 2200 GP pressure sensor is utilized in this study. It has a measurement range of 0 to 200 kilopascals (kPa) with a precision of ±1.5% of the full-scale output. The sensor continuously monitors internal pressure changes as the structure rotates. Pressure data and corresponding angular positions are logged by an Arduino Teensy 3.5. The initial air pressure value is set within a range of 0.4–1.5 (bar) for these measurements. The experiment then evaluates the resistance force exerted by the chambers. Finally, the relative torque caused by this resistance is calculated. Fig. 4(b), illustrates the torque arm distances $S1 = 35$ mm and $S2 = 28$ mm at the PIP and MCP joints, respectively.

3.1 Results

To verify the relationship between finger bending and internal pressure, experiments were conducted under varying initial pressures (0.5, 1.0, and 1.5 bars chosen as representative samples) and bending angles ($0° \leq \theta \leq 45°$). Key parameters were continuously monitored and recorded: internal pressure changes within the chambers (tracked by an MPX 2200 GP sensor), bending force, and resulting torsional torque. As can be seen in Fig. 5 and 6, the forward chamber displayed, during bending lower resistance force and internal pressure compared to the backward chamber under identical initial conditions. This is due to the difference in the air hose lengths connected to each chamber. For the forward chamber, the air hose length is 30 mm, and for the backward chamber, it is 20 mm. The forward chamber, with its longer hose, has a larger initial volume when the system is isolated. The near-constant pressure in Fig. 5 up to 15° likely reflects the almost negligible reduction of the distance b between the rigid links L_1 and L_2 confining the deformable chamber in the first part of the bending motion range. The results of the torques for the MCP and PIP joints are depicted in Fig.7. While the forward chamber exhibits slightly lower resistance force compared to the backward chamber due to the length of the air pipe, the opposite trend is observed for torque, attributable to the greater distance from the force application point to the center of rotation.

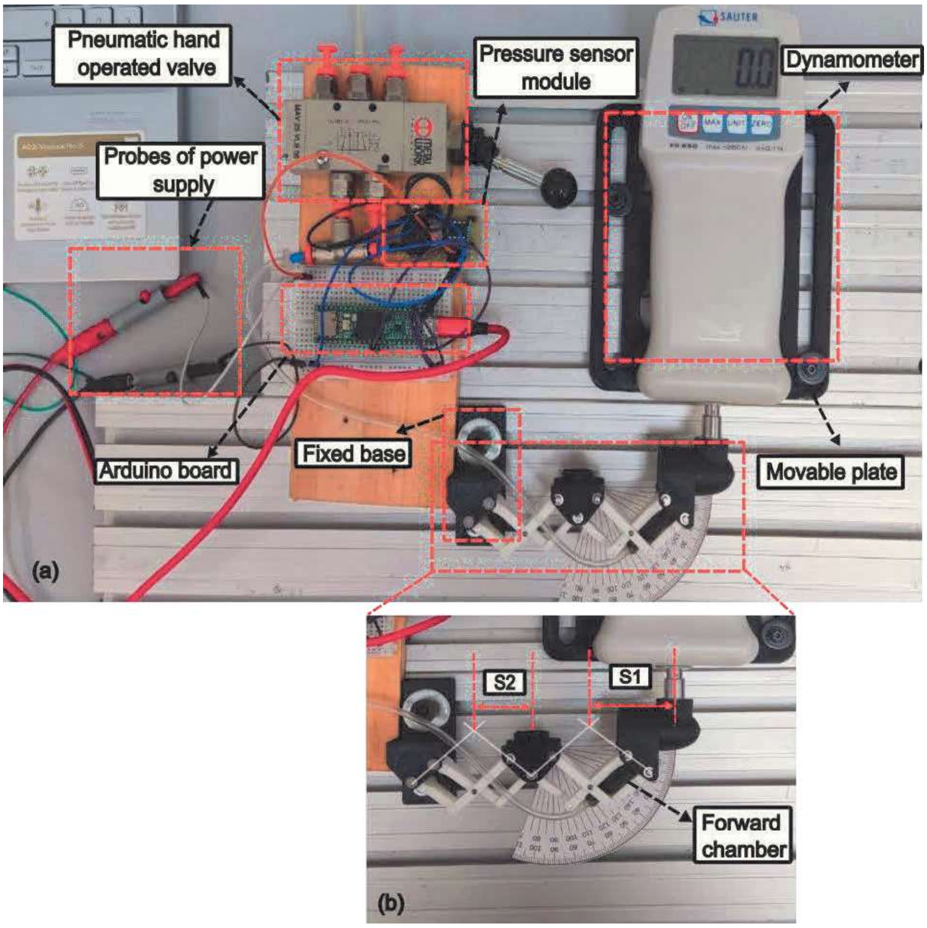

Fig. 4. Experimental setup. (a) the base of the structure was fixed, and the tip and middle part was in contact with the dynamometer. (b) shows the distances for the torque arm at the MCP and PIP joints, respectively.

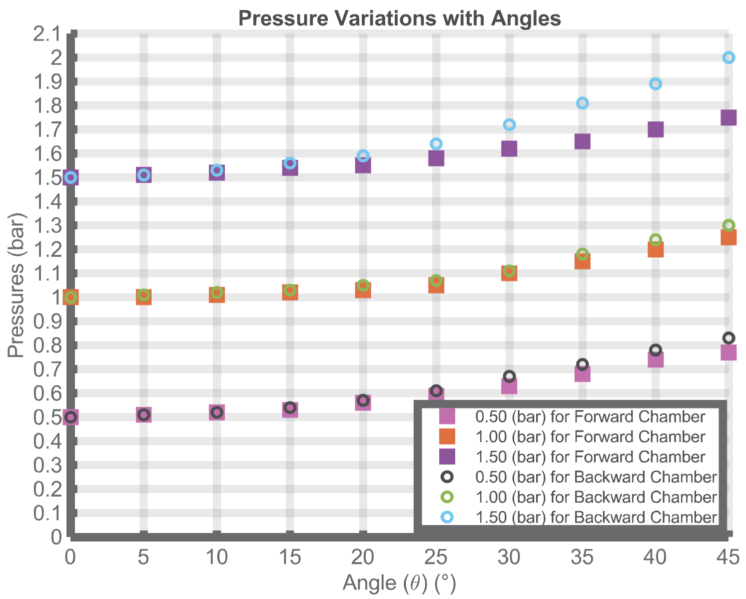

Fig. 5. Internal pressure in forward and backward chambers during structure bending.

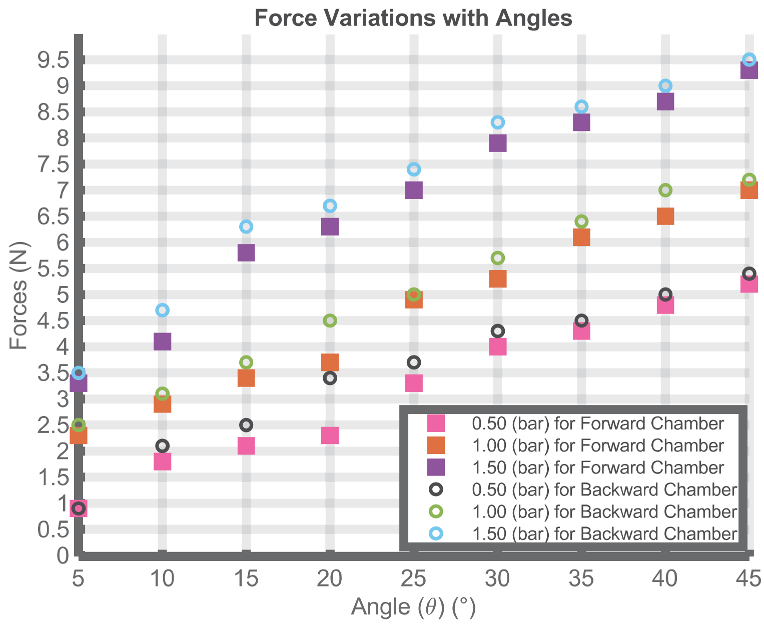

Fig. 6. Comparison resistant force between forward and backward chambers at different bending angles.

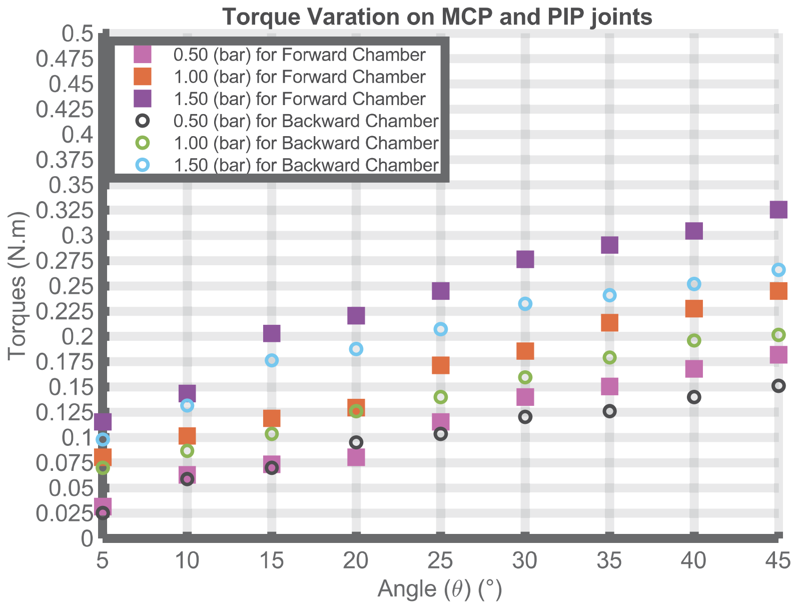

Fig. 7. Comparison torsional torque between MCP and PIP joints at different bending angles.

4 Conclusions

This paper presented a novel wearable glove with inflatable chambers for variable stiffness hand rehabilitation. Despite the double-parallelogram bulk, the device ensures a relative bending motion of 45° between the middle and the inner phalange and between the inner phalange and the palm. Furthermore, the design allows for independent finger and joint actuation and control of resistance force through air pressure. Experimental characterization highlighted the relationship between pressure, force, and torque. These findings provide a foundation for future development of wearable devices for hand rehabilitation. Future work includes a control system for individual chamber pressure, enabling precise stiffness control per joint for targeted rehabilitation exercises.

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